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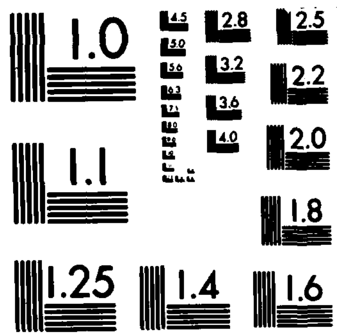

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by

B. A. Kolachev, V. K. Nosov,
et al.

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В в	*В в*	V, v	Т т	*Т т*	T, t
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Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
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Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α	α		Nu	Ν	ν	
Beta	Β	β		Xi	Ξ	ξ	
Gamma	Γ	γ		Omicron	Ο	ο	
Delta	Δ	δ		Pi	Π	π	
Epsilon	Ε	ε	ϵ	Rho	Ρ	ρ	ϱ
Zeta	Ζ	ζ		Sigma	Σ	σ	ς
Eta	Η	η		Tau	Τ	τ	
Theta	Θ	θ	ϑ	Upsilon	Τ	υ	
Iota	Ι	ι		Phi	Φ	φ	ϕ
Kappa	Κ	ϰ κ		Chi	Χ	χ	
Lambda	Λ	λ		Psi	Ψ	ψ	
Mu	Μ	μ		Omega	Ω	ω	

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

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EFFECT OF HYDROGEN ON INDUSTRIAL PLASTICITY OF ALLOY Ti + 9% Al

B. A. Kolachev, V. K. Nosov, V. A. Livanov, G. I. Shchipunov and A. E. Chuchuryukin

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Up to now, hydrogen has only been considered as a harmful impurity which causes hydrogen brittleness. However, in 1957 U. Zwicker and G. Walter established that the addition of hydrogen to titanium alloys raises their plasticity in the hot state [1]. They studied alloys of Ti with 8, 10 and 13% (by mass) aluminum. Alloys

with such a high aluminum content are of great practical interest since ~~they~~ these can be used at temperatures which are unusually high for titanium [2, 3]. Unfortunately, titanium alloys which contain more than 7.5% Al have low technological effectiveness and fracture during hot working. Alloying alloys of the Ti-Al system with hydrogen has made it possible to overcome this defect. With a hydrogen content of 0.505% (by mass), a billet made of a titanium alloy with 8% Al was upset at 950 deg to 78% without crack formation. The billet which did not contain hydrogen fractured under the same conditions. The titanium alloy containing 13% Al was saturated with hydrogen to 0.24%. At 950 deg and a deformation ratio of 69%, insignificant spalling was observed on the upset billet. In this case, the billet which did not contain hydrogen was completely destroyed during forging.

However, not one study has been published in this area since 1957. The purpose of this research was to study the technological plasticity of a titanium alloy alloyed with 9% Al in a broad range of hydrogen contents (0.006-0.3 weight %) at hot working temperatures.

Keywords: Translations; USSR; foreign technology

Alloy Ti + 9% Al was made from titanium sponge TG-105 and aluminum brand A7. A 5 kg ingot was melted in a vacuum furnace with a consumable batch electrode. The ingot was melted twice to obtain a

more homogeneous composition. The alloy was studied in the cast state. Cylindrical specimens 20 mm in diameter and 15 mm high were turned from the ingot.

The specimens were saturated with hydrogen in the equipment described in [4]. Before hydrogen absorption, the specimens were brought to the identical initial state by vacuum annealing for 2 hours at 800°.

The specimens were placed in a container made of refractory steel and loaded into the furnace. After the furnace reached the assigned temperature, the container with the specimen was held for 30-40 minutes and transferred to the test machine. 1-1.5 minutes elapsed from the time the container with the specimen was removed from the furnace until the tests were completed. During this time, the temperature of the specimen remained virtually constant.

The technological plasticity and nature of fracture were estimated by determining the alloy's plasticity when testing the specimens by upsetting until the first crack which could be seen by the naked eye appeared. The specimens were upset in a UMM-5 machine

with a crossbar which moved at a speed of 10 mm/min. When the load exceeded 5 tons, the tests were conducted on hydraulic press PMM-125 with a force range of up to 125 tons. Furthermore, part of the specimens were subjected to dynamic upsetting on air hammer PM-50 with falling parts weighing 50 kg.

X-ray investigations were carried out in a KROSS chamber with a flat housing. The X-rays were taken in copper K_α radiation with a nickel filter.

These upsetting tests[1] showed (Fig. 1) that the plasticity of alloy Ti + 9 % Al is very low at temperatures up to 1100°. [Footnote: [1]N. V. Yermishin participated in the experimental part of the research. End footnote] Cracks already appear on the sides of the specimen at a 50% deformation ratio and an upsetting temperature of 1050°, which corresponds to the α-region of the Ti-Al phase diagram for this alloy. Reducing the temperature to 1000 and 950° decreases the critical deformation ratio to 38 and 25% respectively. High deformation resistance is typical of alloy Ti + 9% Al. At a deformation temperature of 950°, the specific pressure is 27 and 32 kg/mm², respectively, for upsetting at 25 and 50% (Fig. 2).

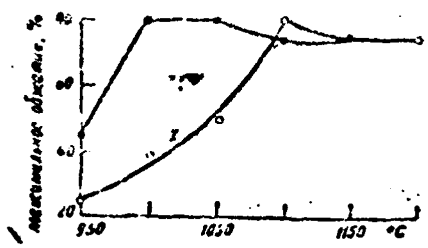

Fig. 1. Dependence of technological plsticity of alloys Ti + 9% Al + 0.1% H_2 (1) and Ti + 9% Al (2) on temperature.

KEY: (1) Maximum compression.

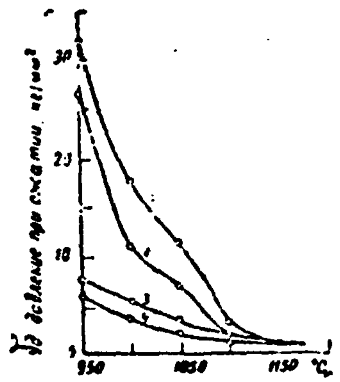

Fig. 2. Specific pressures during compression of alloy Ti + 9% Al depending on temperature and content of hydrogen:

KEY: (1) Specific pressure during compression, kg/mm².

Raising the deformation temperature to 1100° (this temperature is close to the boundary of the $\alpha + \beta/\beta$ transition) results in an anomalous surge in the plasticity of alloy Ti + 9% Al with signs of superplasticity which are typical of alloys with polymorphic transformations [5]. The reserve of plasticity in a specimen upset by 75-80% is far from exhausted; the specific pressure during compression is 3-4 kg/mm² for a specimen deformed by 50% (see Fig. 2).

During upsetting at temperatures which correspond to the β-region (1150-1200°), the alloy is deformed to high deformation ratios without destroying its integrity. However, there are sharp protrusions and tears along the grain edges on the sides. The critical deformation ratios turn out to be lower at 1150-1200° than at 1100° (see Fig. 1).

When 0.1% H_2 is added to the alloy in question, the critical deformation ratio at 950° increases to 45% versus 25% for the alloy without hydrogen (see Fig. 1). Increasing the temperature to

1000-1050° makes it possible to deform specimens by 75-80% or more. Deformation of the alloy with 0.1% H_2 at 1100° occurs analogously to that of the specimens without hydrogen at 1150-1200°.

During dynamic upsetting on an air hammer, specimens of alloy Ti + 9% Al fractured by spalling after 50% deformation. On the other hand, specimens containing 0.1% H_2 withstood upsetting at the same temperature by 80-90% without signs of fracture. Raising the dynamic upsetting temperature to β-region temperatures (1150-1200° for alloy Ti + 9% Al) causes cracks and tears to appear on the sides at a deformation ratio of around 75%. With consideration of the results of a number of published reports, this makes it possible to establish a critical deformation ratio of 75% for these temperatures and alloys (see Fig. 1).

Hydrogen considerably reduces the deformation force (see Fig. 2). Thus, at an upsetting temperature of 950° and a deformation ratio of 25% the specific pressure during compression is 6 kg/mm^2, i.e., almost 5 times lower than for the alloy without hydrogen. Hydrogen decreases the deformation force up to 1100°; at higher temperatures, the forces become approximately equal for the alloy with hydrogen and without it.

The effect of different hydrogen contents on the technological plasticity of alloy Ti + 9% Al was studied at 950°, when the critical deformation ratio for the alloy with 0.006 H_2 is 25%, and for the alloy with 0.1% H_2 - 45 . Figure 3 generalizes the results of upsetting cylindrical specimens on the test machine and the air hammer. The permissible deformation ratios increase up to hydrogen contents of 0.15-2.0%. The specimens with these hydrogen concentrations were deformed by 80% without any traces of fracture. Further increasing the hydrogen content in the alloy reduces its technological plasticity. Thus, the permissible deformation ratio for an alloy with 0.25% H_2 is 60% and for an alloy with 0.3% H_2 - 40%. Fracture of specimens with 0.25-0.3% H_2 is intracrystalline, as opposed to the intercrystalline fracture of specimens with a H_2 concentration of 0.1%.

The specific pressure during 50% deformation of the alloy with 0.15% H_2 is half that of the alloy with 0.1% H_2. The decrease in deformation resistance is retained when the hydrogen content is increased to 0.3%. According to the Ti-Al phase diagram, the structure of the alloy is represented by the α-phase and a small

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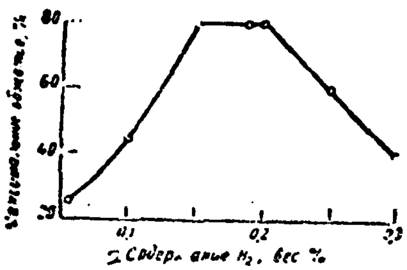

Fig. 3. Dependence of technological plasticity of alloy Ti + 9% Al at 950° on hydrogen content.

KEY: (1) Maximum compression. (2) H_2 content, weight .

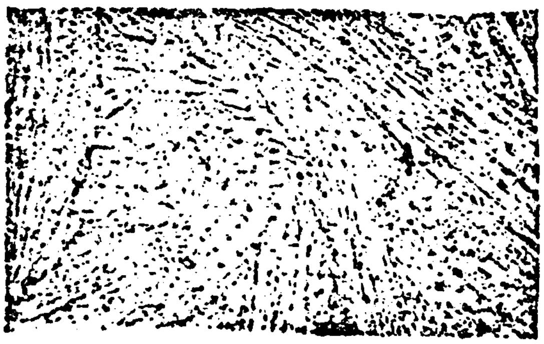

Fig. 4. Microstructure of upset specimen of alloy Ti + 9% Al after 45 deformation at 1050°. x200.

quantity of secondary α_2-phase in the form of a fine network on the α-phase boundaries in the initial state (0.006% H_2). When the alloy is saturated with 0.1% H_2, the microstructure remains virtually invariable, except that the intragrain substructure is revealed more clearly and the specimen becomes more etchable. With the further increase in the hydrogen concentration, the intragrain substructure becomes finer and etching reveals an overall gray background. Therefore, the specimen must be lightly polished after etching in order to reveal its structure.

Alloy Ti+9%Al deformed at 950-1050° has many internal flaws (Fig. 4) which are located in the places where three grains join, but they are also found on the boundaries between two grains. The specimens deformed at 1100 and 1150° do not have microscopic flaws, their structure being represented by the β-transformed phase.

After deformation in the temperature range from 1000-1150°, the specimens with 0.1% H_2 do not have any microscopic flaws. The microstructure of the alloy changes markedly at a deformation ratio of 50% beginning with 1050°. It looks like the transformed β-phase with acicular structure. As the temperature increases, the acicularity of the structure is more clearly visible. The deformation

ratio has the same effect. According to our observations, this type of structure is not observed at a deformation ratio of 50% and a temperature of 1050-1100°, while at the same temperature and a deformation ratio of 75%, clearly expressed acicular structure forms.

In order to determine the completeness of recrystallization, the deformed specimens were studied by X-ray analysis. The results of the X-ray analysis of specimens of the alloy with 0.006 and 0.1% H_2 deformed by 50% showed that the alloy with 0.006% H_2 deformed at 950° has nonrecrystallized structure. The unbroken interferential rings in the X-rays with no traces of branching into separate reflexes indicate this. Completely recrystallized structure is observed in the specimen deformed at 1100°.

The X-ray of the specimen deformed at 1150° indicates a less recrystallized structure than that of specimen deformed at 1100°. This can be explained by the fact that 1100° is close to the temperature of the $\alpha+\beta \rightleftharpoons \beta$ transformation and that recrystallization is accelerated during deformation accompanied by a phase transformation.

The hydrogen in alloy Ti + 9% Al lowers the temperature of the beginning of recrystallization. Partially recrystallized structure is observed in the specimen with 0.1% H_2 deformed at 950°, while recrystallization is already complete in the specimen deformed at 1000°. By analyzing the X-rays we find that the alloy with 0.1% H_2 is in a more stressed state than the alloy with 0.006 H_2 deformed under the same conditions. The reflexes are more blurred in the X-rays of the alloy with hydrogen than in those of the alloy without it. The results obtained in this report confirm the data given in the patent [1] which state that hydrogen raises the deformability of titanium alloys with a high aluminum content in the temperature range used for hot working.

A favorable effect of 0.1% H_2 on technological plasticity is observed up to 1100°. Above this temperature, the permissible compression is virtually identical for specimens with and without hydrogen. The greatest technological plasticity is observed in a specific temperature range. This temperature is close to 1100° for alloy Ti + 9% Al. Hydrogen lowers this temperature and expands the temperature range in which the maximum plasticity is manifested. There is no doubt that the reduction of the temperature and working force is often desirable and has practical applications. Of course, after the favorable effect of hydrogen on the technological

efficiency of the alloys is used, it must be removed from them by vacuum annealing in order to avoid hydrogen brittleness.

One possible hypothesis of the mechanism of this hydrogen effect can be summed up as follows. In report [6], I. I. Kornilov et al. proved that titanium alumide with the composition Ti_3Al exists in the Ti-Al system. Increasing the aluminum content in titanium alloys results in the supersaturation of the solid solution α and the separation of dispersed α_2-phase particles from it based on intermetallide Ti_3Al. These particles inhibit sliding on the grain edges, as well as within them. This causes plasticity to drop at temperatures below the dissolution temperature of titanium aluminide Ti_3Al. Clearly expressed intergranular fracture is manifested and the individual grains are clearly visible on the surface of the specimens after compression.

Hydrogen inhibits the formation of grain-edged α_2-phase separations, which is responsible for the brittle fracture of alloy Ti + 9% Al during deformation. Fracture becomes intracrystalline and viscous.

The suppression of phase separation when alloying alloy Ti + 9% Al with hydrogen is not the only reason for raised technological effectiveness. An anomalous surge in technological effectiveness similar to the phenomenon of superplasticity which was first studied in detail by A. A. Bochvar [7] even occurs during compression in the alloy without hydrogen at temperatures close to the $\alpha + \beta/\beta$ phase transition.

Hydrogen facilitates the conditions for the development of the anomalous surge in technological effectiveness related to the superplasticity effect in alloy Ti + 9% Al during the phase transition. The addition of hydrogen not only raises the permissible compression, but also markedly decreases the deforming forces.

There are at least two reasons why hydrogen can contribute to the development of superplasticity: being a β-stabilizer, hydrogen lowers the temperature of the $\alpha + \beta/\beta$ transition; therefore, the plasticization effect is manifested at lower temperatures in hydrogen-saturated specimens. Secondly, hydrogen has diffusion coefficients which are several orders of magnitude higher than the those of the other elements. Thus, at 1000° the diffusion coefficient of hydrogen in β-titanium is 10^{4} times greater than the coefficient

of self-diffusion. Weight concentrations of hydrogen on the order of 0.15-0.20% correspond to 5-10 atomic %. At such high concentrations, hydrogen cannot help but have an accelerating effect on the diffusion of titanium atoms, although it is an interstitial admixture.

Hydrogen has the most favorable effect at 950° in the range of concentrations from 0.15-0.2%. At both lower and higher hydrogen concentrations, the plasticization effect decreases for two reasons: at hydrogen contents below 0.15% the temperature range in which superplasticity is manifested is higher than 950°, and at contents greater than 0.2% - lower. When the hydrogen contents are too great, the harmful effect of hydrogen dominates - hydrogen brittleness begins to develop.

Conclusions

1. The study confirms data on the favorable effect of hydrogen on the technological plasticity of alloys with a high aluminum content at hot working temperatures.

2. The favorable effect of hydrogen is not only expressed by lowering the temperature of the anomalous surge in plasticity related to the $\alpha+\beta \rightleftarrows \beta$ (around 1100° for alloy Ti + 9% Al), but also in the extension of the temperature range of increased technological effectiveness during upsetting from 1000 to 1050°.

3. The positive effect of hydrogen is also manifested in a considerable reduction in the deformation forces throughout the range of temperatures and hydrogen concentrations in question.

4. Hydrogen has the most favorable effect in the range of concentrations from 0.15-0.2% (by mass).

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